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15 April 1980

Technical Report

Prepared for:

OFFICE OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY
ARLINGTON, VA 22217

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ABSTRACT

A HIGH RESOLUTION, LOW FREQUENCY PARAMETRIC SYSTEM FOR OCEANOGRAPHIC RESEARCH

by

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Applied Research Laboratories
The University of Texas at Austin

The development and application of a parametric acoustic array system is described. Key features include a 720 element primary projector measuring 2.3 m in diameter, with a fundamental resonance in the 11-16 kHz band. Eighty kilowatts of primary pulse power are applied to this array to develop difference frequency radiations in the 500 Hz to 5 kHz band. Half-power beamwidths of the primary and difference frequency radiations are on the order of 2.5°. An array of 30 low frequency elements is interleaved in the primary array for reception of the difference frequency echoes as well as for transmission of linear signals in this band. The system has a capability for alternate parametric and linear transmission to enable near simultaneous acquisition of parametric and linear data. A capability for sequentially stepped center frequencies is also provided for near simultaneous frequency response measurements. Shaped pulse (i.e., gaussian, box-car, etc.) as well as variable bandwidth FM pulse operation is also provided. Mechanical features include mounting on an offshore platform with continuously variable transducer tilt, train, and depth positioning, as well as VDS towing in a spherical fish with rope fairings. Application of the system to environmental acoustics research is also described.

I. INTRODUCTION

There are two general types of active acoustic systems used to image objects and structures in the field of view. These are: 1) seismic systems which are generally non real time devices used to examine structures that do not move and 2) sonar systems which are usually real time systems used against targets which are often in movement. Although there are some similarities between these two type of systems they actually have very little in common.

The seismic systems achieve their resolution by successive relocation of both sensors and sources, while viewing the same general area. This is made possible by the static nature of the structures being examined. In this way, excellent effective angular resolution can be achieved merely by building up very large arrays through successive relocation of sensors.

In contrast, the sonar situation involves real time echo location and/or imaging with a physical array of sensors. Angular resolution is solely a function of the size of the array and the operating frequency. The resolution problem reduces to the tradeoff between how big an array can be accommodated and the choice of the frequency at which the array is operated. Higher resolution is achieved as the frequency is increased but longer ranges are achieved as the frequency is decreased.

Up to now, the word "high resolution" when used in conjunction with sonar systems has usually meant a device operating in the neighborhood of 100 kHz or above with effective half power beamwidths on the order of a degree or so. These devices are commonly used as side scan sonars in offshore mapping, object searching, bottom topography, etc.

This paper describes a system which achieves the same order of high angular resolution at frequencies two decades lower than existing high resolution sonar systems. The technique utilized is nonlinear parametric sonar. Parametric systems are well known in hydrographic sonar work but are not widely appreciated in seismic technology. For this reason, the principle of the parametric technique will be explained.

II. PARAMETRIC ARRAYS

The fundamental processes of a parametric array are sketched in Fig. 1. A source simultaneously emits two high frequency primary waves at frequencies f_1 and f_2. These beat together in amplitude modulation. Nonlinear interaction occurs in a zone encompassed by the primary beams out to the range where the primary waves are absorbed. Each elementary volume in this irradiated zone becomes a nonlinear oscillator producing vibrations at the sum and the difference of the two original frequencies. The difference frequency radiation is of practical significance because of its high directivity, which is achieved at low operating frequencies. Large bandwidths, useful in signal processing, can also be achieved by this technique. The main advantage of the parametric technique is that it produces a radiation pattern at the difference frequency which is highly directive and is completely devoid of undesirable minor lobes. The main disadvantage of the technique is that it is one of low conversion efficiency. These topics will be addressed in the discussion of the present system.

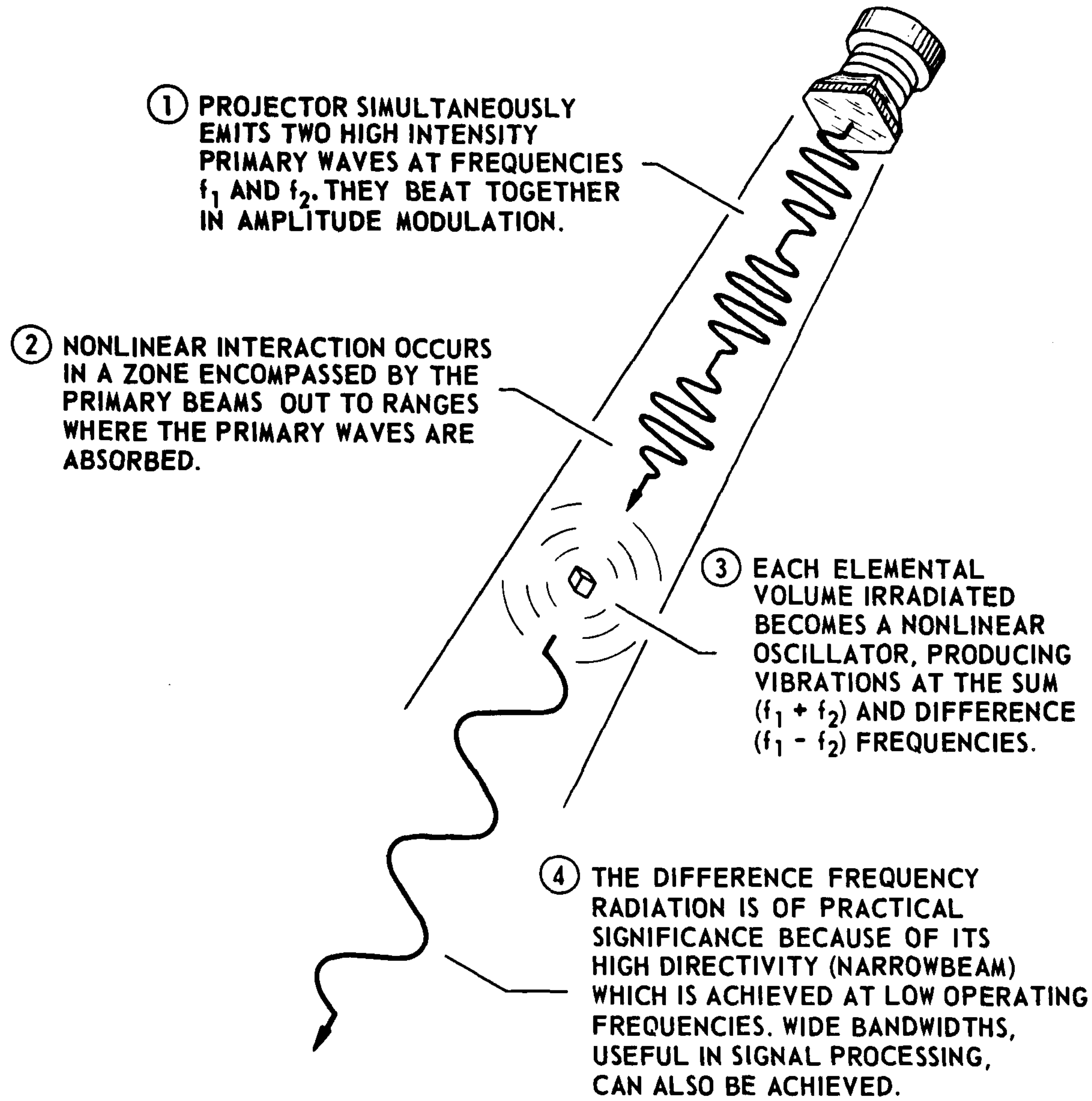

FIGURE 1
PROCESSES IN A PARAMETRIC TRANSMITTING ARRAY

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III. THE PRESENT SYSTEM

Research and development on parametric arrays has progressed to the point where large systems for applications in ocean acoustics can be considered. The system described in this paper was intended as a research tool for a wide variety of measurements in shallow water over the continental shelf. A photograph of the transducer is shown in Fig. 2. It is a circular piston array 2.3 m diam, operating at primary frequencies in the neighborhood of 12.5 kHz, with difference frequencies in the neighborhood of 500 Hz to 5 kHz. Through nonlinear processes in the water, the 12.5 kHz radiation also produces energy at its harmonic frequencies. The transducer array consists of 720 mass loaded elements. Alternate elements are driven at slightly different frequencies centered around the primary center frequency to generate the two frequencies in the water which then interact to produce the difference frequency radiation. The circular holes in the transducer backplane are provided to house low frequency elements designed to receive echoes from the parametric difference frequency radiation as well as to transmit signals linearly in the low frequency band. These devices were not installed when the photograph was taken. These are also mass loaded elements with a resonance at 2400 Hz. The arrays are mounted on a stainless steel backing plate. Located behind the array is a canister to house matching transformers and miscellaneous electronics fixtures. The array and the canister with elements installed weighs approximately 11 kg.

Before discussing the performance of this array it is instructive to discuss the electronic components of the system. A block diagram of the transmitter is shown in Fig. 3. This diagram indicates 20 staves each consisting of 18 primary frequency elements driven at f_1, with 20 identical staves of 18 elements each driven at primary frequency f_2. As previously stated, adjacent elements in the array are driven at different frequencies, either f_1 or f_2. Each stave of 18 elements is driven by a two kW power amplifier and the system is configured so that there are 20 two kW amplifiers at f_1 and 20 two kW amplifiers at f_2 all driven in

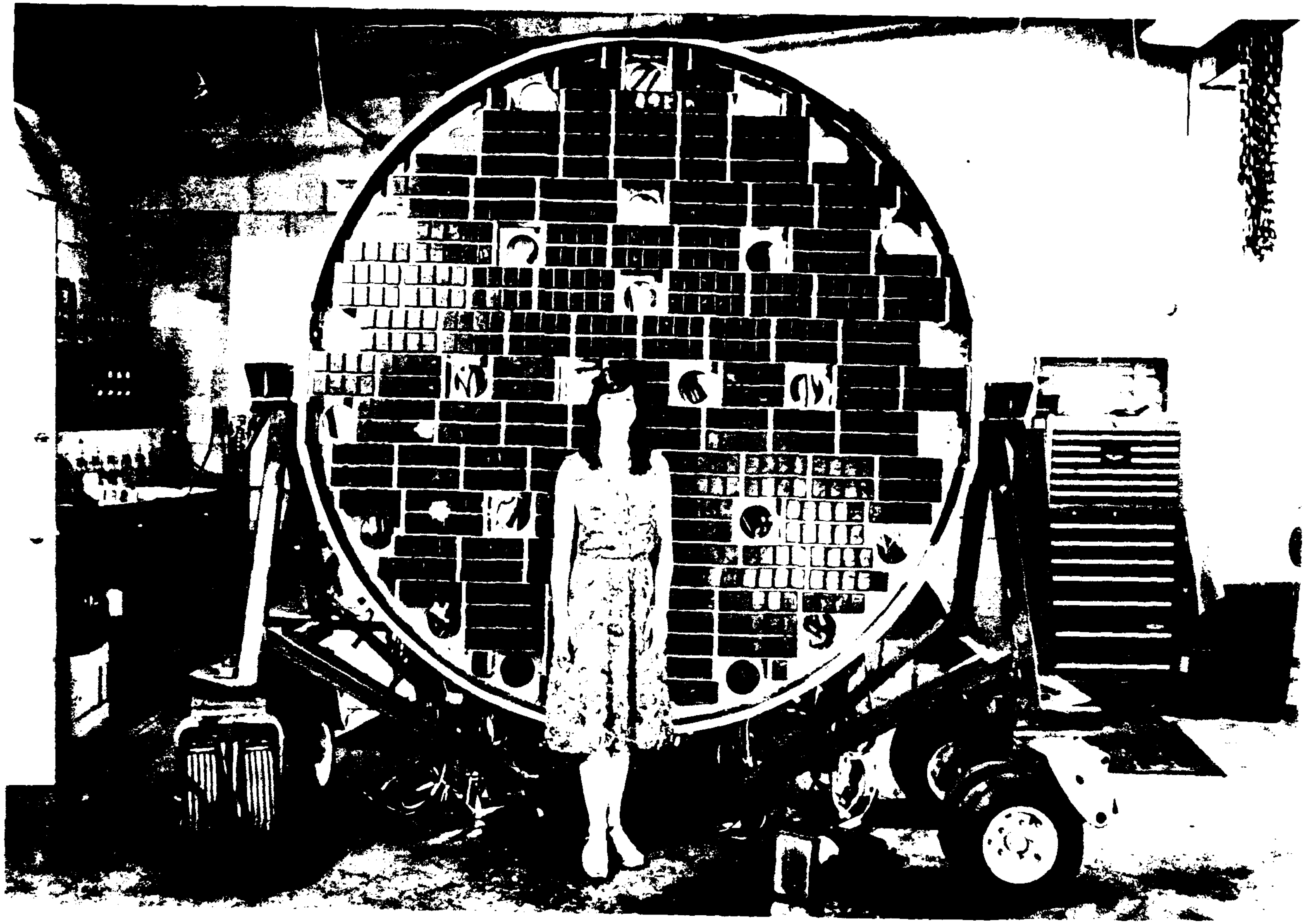

FIGURE 2
TRANSDUCER ARRAY

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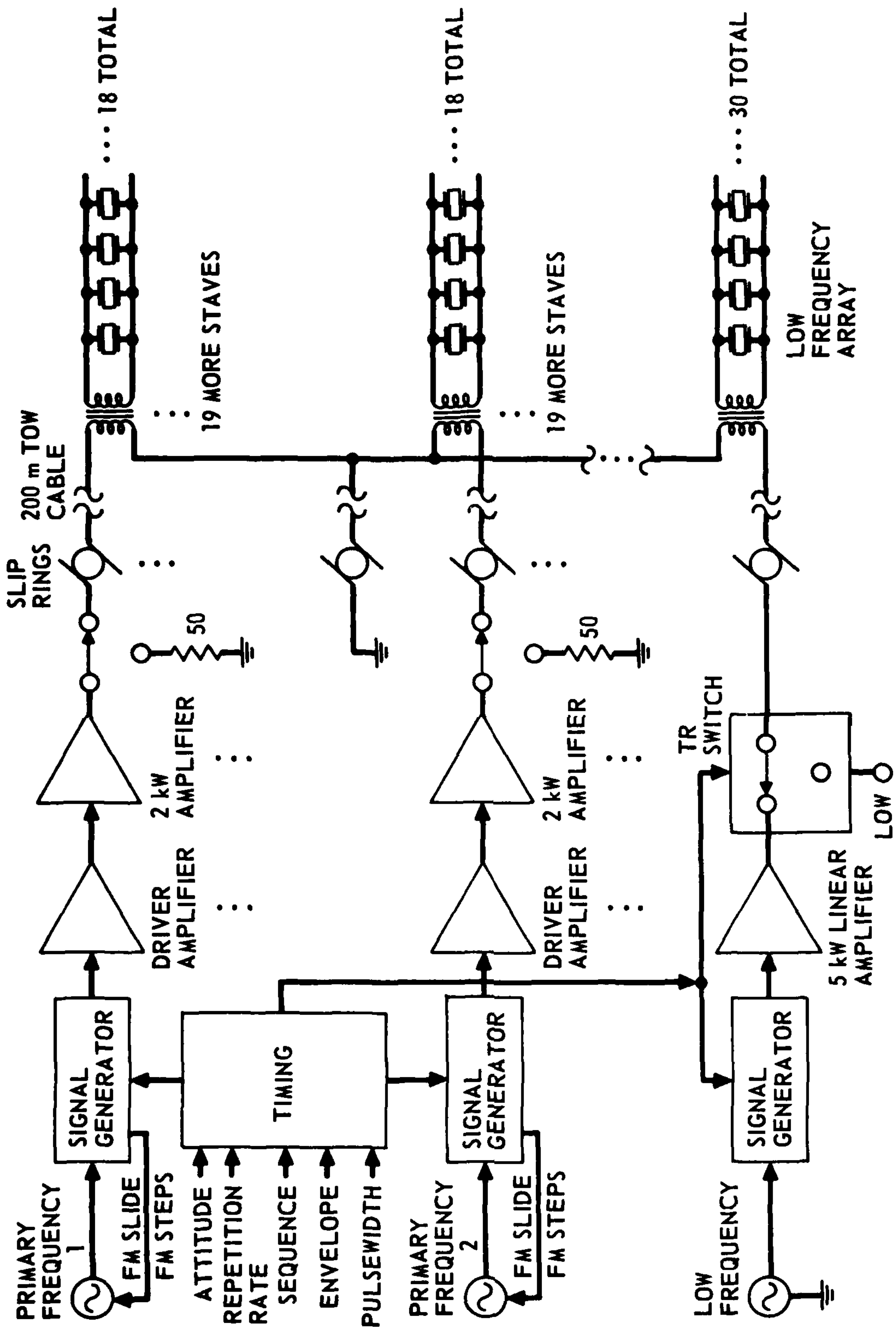

FIGURE 3
TRANSMITTER BLOCK DIAGRAM

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parallel. The signal generator for each primary frequency consists of a micro-computer controlled oscillator that permits automatic selection of a wide variety of pulse shapes and pulse types. For example, a primary frequency can be sequentially varied in ten steps from pulse to pulse, starting at a low frequency and progressively stepping to higher frequencies to provide the experimenter with sequentially changing difference frequencies in the water. Capabilities for FM chirp and CW pulses are also provided. Swept bandwidth can be varied from a few hundred hertz out to a FM slide of 5 kHz. Sequential operation enables experiments to be done essentially simultaneously at different frequencies to permit the frequency dependence of an experiment to be determined very quickly. For linear transmissions the same kinds of signals can be applied to the low frequency array through a separate 5 kW low frequency driver system as shown at the bottom of Fig. 3. Provision is made for alternately exciting parametric and linear sources in the aforementioned stepped frequency pulse sequence.

A sketch of the transmitter system is shown in Fig. 4. The electronics is mounted in two separate mobile enclosures. To conserve funds the transmitter was constructed of components from several existing U.S. Navy fleet sonars. It is built around a vacuum tube type power amplification system. The motor generator hut shown at left in the figure houses devices to convert 440 Vac to 5400 Vdc plate supply voltage; these are the main motor generator sets. This hut also houses auxiliary motor generators that provide the voltages needed for screen, grid, and filament supplies. The transmitter hut houses various controller devices as well as three stacks of power amplifiers consisting of 40 two kW power amplifier modules which supply a total of 80 kW of electrical power. This hut also contains auxiliary equipment, including a dummy load as well as the 5 kW power amplifier used to drive the low frequency linear elements.

Initial experimentation will be performed using a fixed platform, the Stage I facility of Naval Coastal Systems Center, Panama City, Florida. This facility is depicted in Fig. 5. It is located

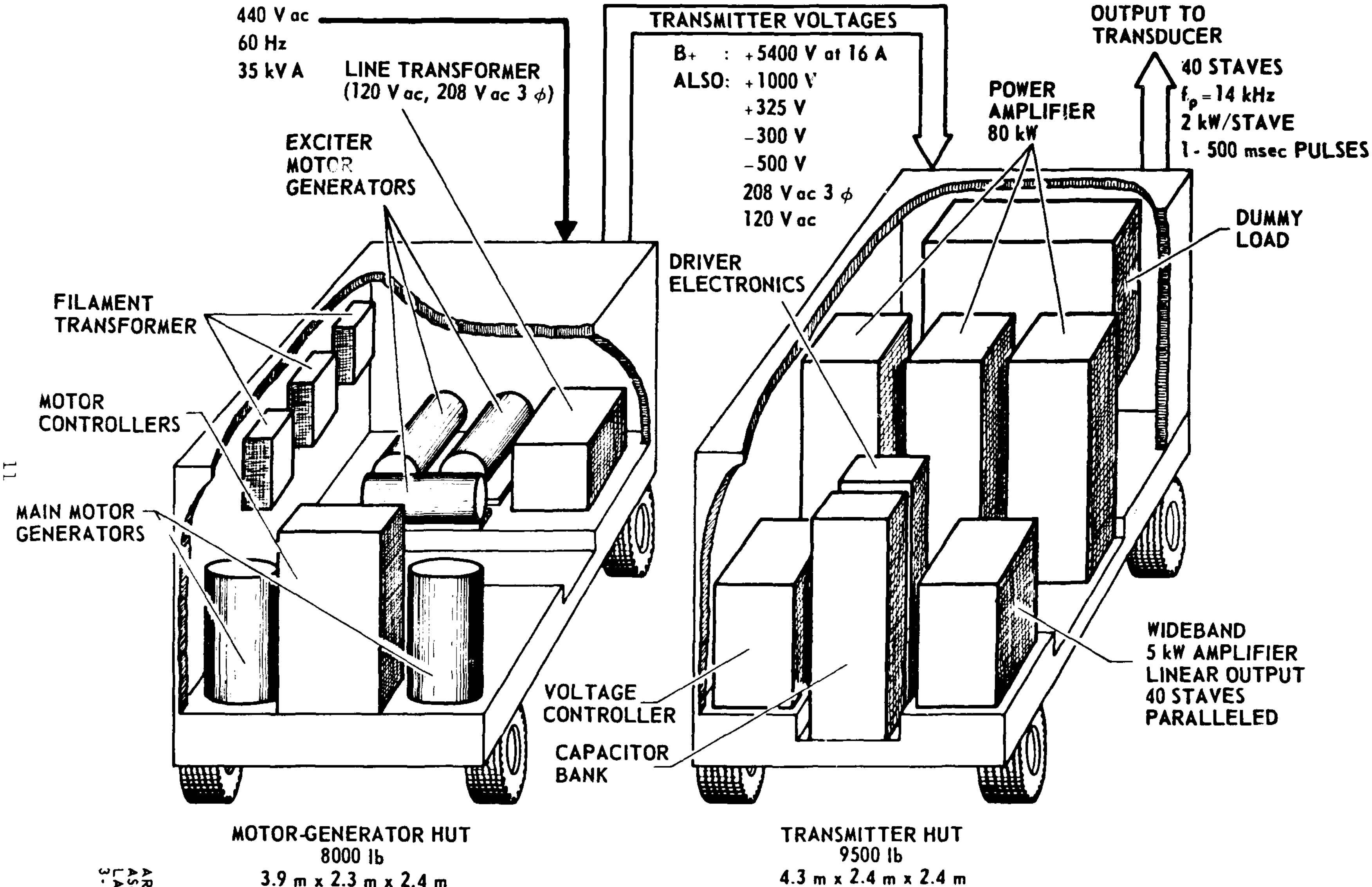

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FIGURE 4
TRANSMITTER ELECTRONICS EQUIPMENT

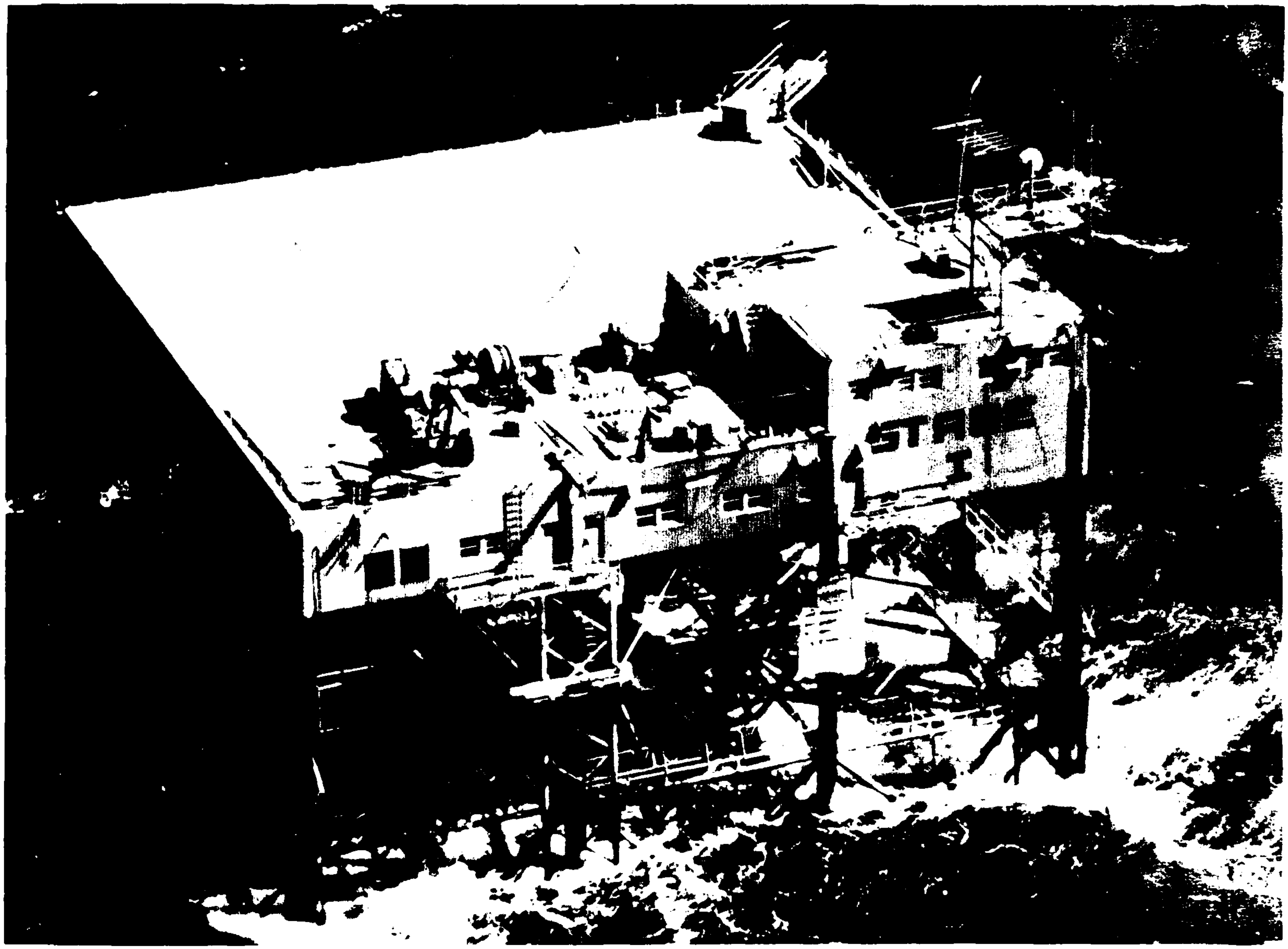

FIGURE 5
STAGE I INSTALLATION

approximately 20 km offshore in approximately 34 m deep water. The platform is about 30 m on each side. The transmitter electronics huts will be mounted on deck, and the transducer will be mounted on the rail-guided elevator seen near the left side of the near face of the platform. The fixed platform tests will be followed by mobile tests aboard a research vessel with the system configured as a variable depth sonar.

The tests will allow limited but controlled shallow water studies to be done first to isolate and assess essential parameters without the mitigating effects of ship motion and/or changing geographical conditions. Once the key features of the study are identified, specialized experiments will then be conducted aboard the research vessel to ascertain how the findings from the fixed platform study stand up underway.

IV. SYSTEM PERFORMANCE

Before moving this equipment to Florida, several measurements of its acoustic properties were made in fresh water at Lake Travis near Austin, Texas. Representative radiation patterns are shown in Fig. 6. On the left is the pattern for a 13 kHz primary radiation obtained from linear operation of the f_1 array. Next to this pattern is a 2 kHz difference frequency pattern obtained by driving the system at 12 and 14 kHz and allowing the 2 kHz to be generated in the water through parametric interaction. Notice the narrow beamwidth as well as the complete absence of minor lobes. The pattern on the right is that obtained from 2 kHz linear emission by the array of conventional low frequency elments. Notice the considerably broader major lobe, as well as the existence of minor lobes in this radiation pattern. One of the major advantages of nonlinear acoustics is illustrated in the comparison of the two patterns at 2 kHz: with a parametric beam one realizes superdirective radiation without minor lobes, which is ideal for viewing targets as well as for suppression of reverberation.

A comparison of half-power beamwidths versus frequency for the parametric and linear arrays is shown in Fig. 7. The linear radiation has a half-power beamwidth around 80° at 500 Hz which decreases with increasing frequency to about 8° at 5 kHz, a decade change in frequency. On the other hand the parametric radiation has a relatively constant beamwidth, shown here to be approximately 4°, over the same frequency range. These data were taken at a nearfield range of only 80 m. In the farfield the parametric beamwidth should decrease to approximately 2.5° and remain constant over the 500 Hz to 5 kHz frequency range. The fact that the narrow beam parametric radiation can be designed to have a constant beamwidth over a decade of frequency change makes it an excellent research tool for conducting a wide variety of experiments. Among these are measurements of reverberation, bottom penetration, scattering, and mode selection in the shallow water waveguide.

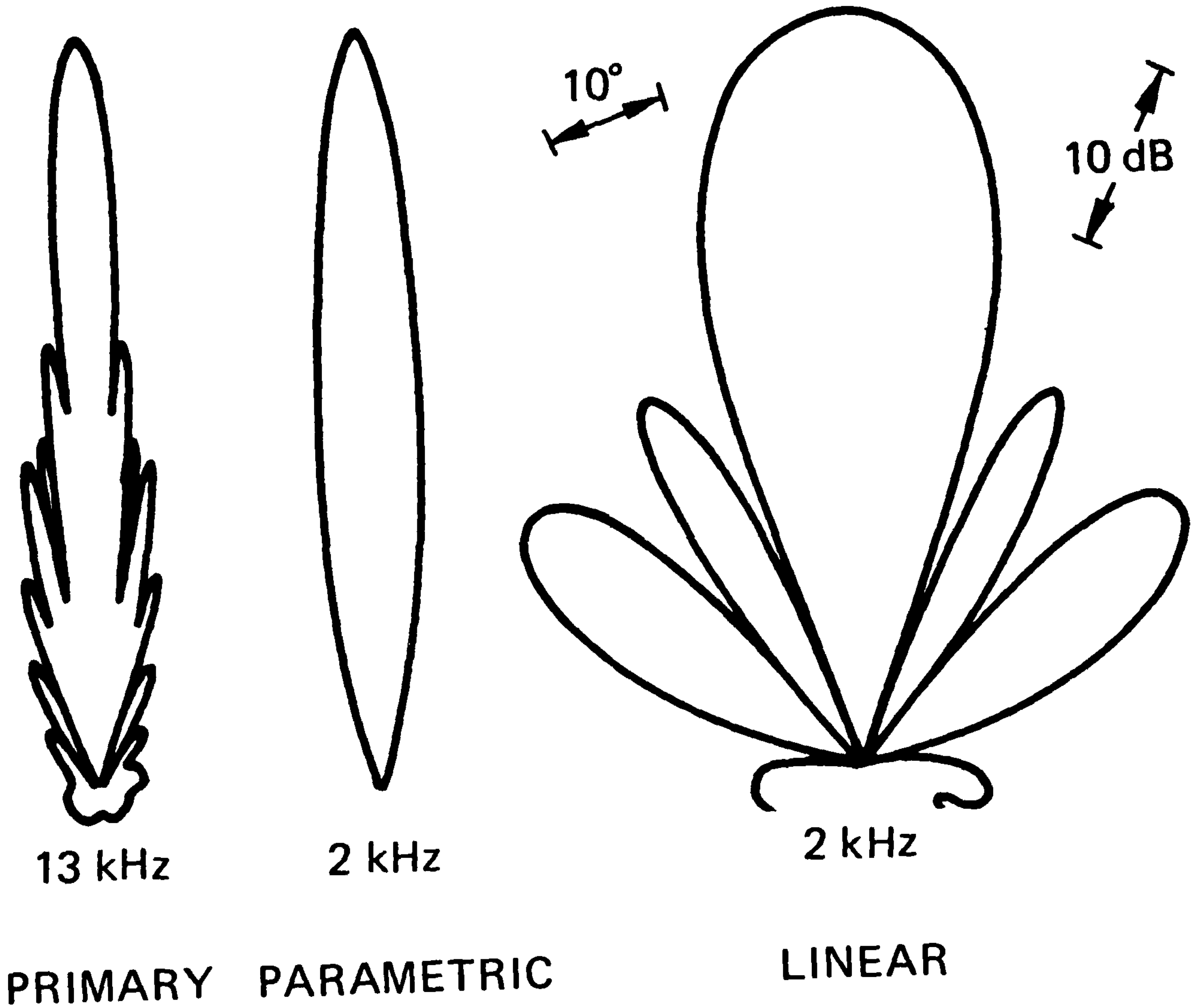

FIGURE 6
BEAM PATTERNS

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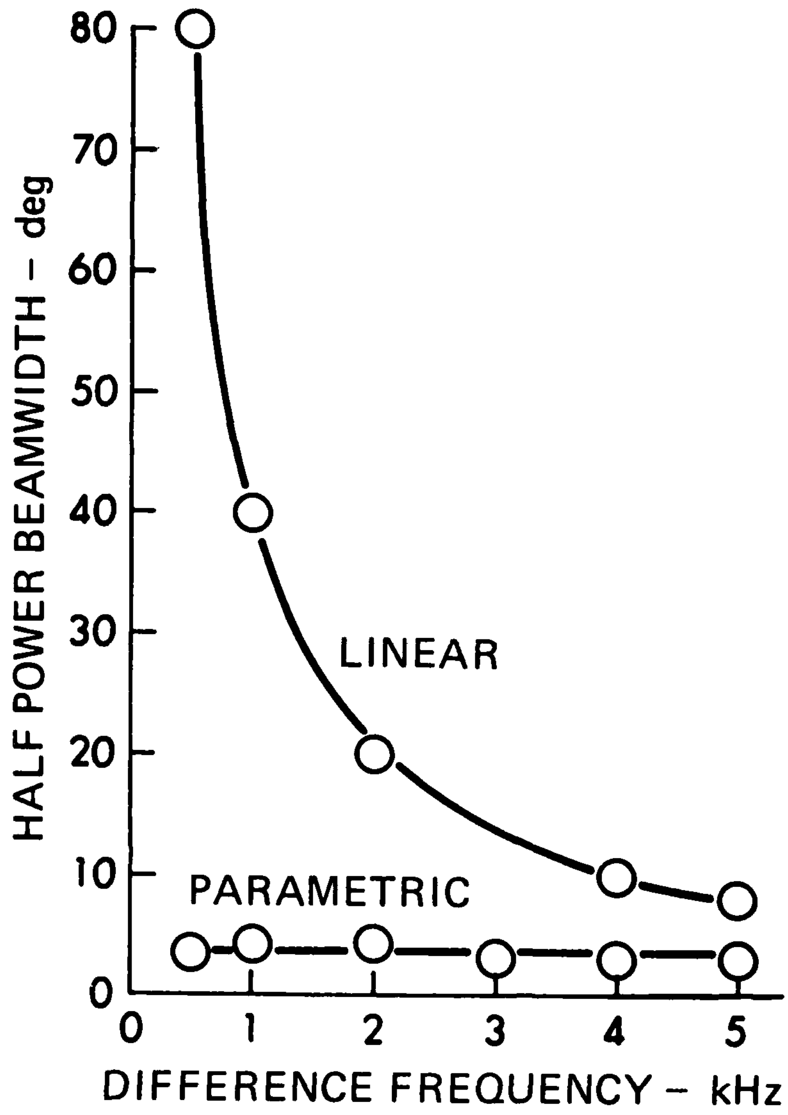

FIGURE 7
BEAMWIDTH CHARACTERISTICS

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Measurements of source level versus frequency of the system are shown in Fig. 8. The primary frequency source level is in the neighborhood of 250 dB re 1 μPa at 1 m over the frequency range 10 to 16 kHz. Difference frequency source levels, extrapolated from nearfield measurements at 80 m, vary from about 88 dB to 112 dB re 1 μPa at 1 m over the same frequency range. This variation occurs because the parametric interaction process improves in efficiency with increase in difference frequency. These data are from measurements made within the growth region of the parametric interaction volume. Values extrapolated from farfield measurements should be considerably higher, probably at least 10 dB.

Characteristic waveforms for radiation from this high intensity parametric source are shown in Fig. 9. Shown are primary frequency signals as a function of radiated acoustic power. With only 10 kW radiated power, a near sinusoidal waveform is produced. At 20 kW, the waveform is distorted, and at 40 kW radiated power shock waves are evident. Steep discontinuities occur at the shock front and asymmetry between the positive and negative pressure portions of the wave occurs. This asymmetry is the subject of studies in nonlinear acoustics centered around the role of diffraction in the distortion process. Shock waves are the hallmark of nonlinear sonar. The reason that shocked waveforms are desired is because they contain useful harmonic radiations. A Fourier analysis of the waveforms of Fig. 9 will show the existence of a series of harmonic radiations which are useful both in sonar research and in sonar applications.

The utility of harmonic radiation is demonstrated in Fig. 10 which compares the radiation pattern of the system operated at the fundamental, or first harmonic, shown on the left, with the pattern at the second harmonic, center, and at the third harmonic, right. The patterns become progressively narrower and minor lobe suppression increases with increase in harmonic number. Theoretically it has been shown that the harmonic patterns vary as the fundamental pattern raised to the nth power, n being the harmonic number of the particular harmonic in question.

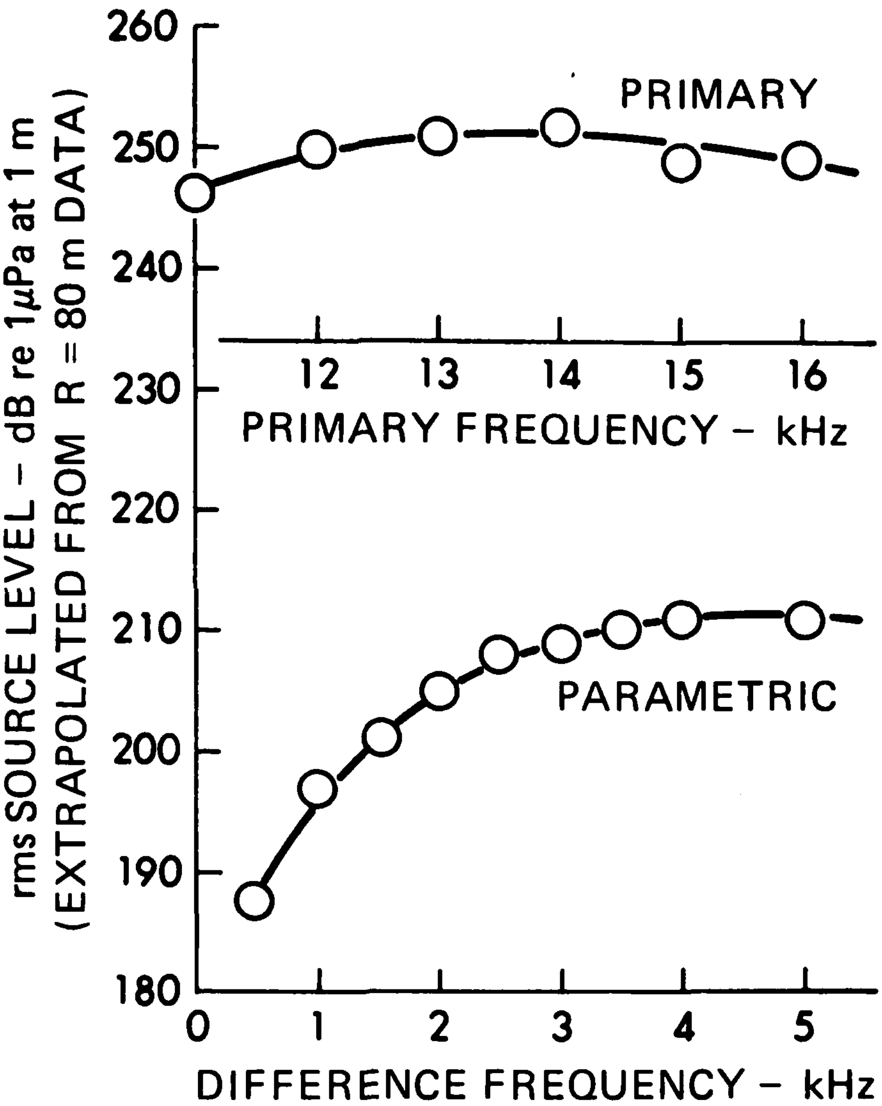

FIGURE 8
FREQUENCY RESPONSE DATA

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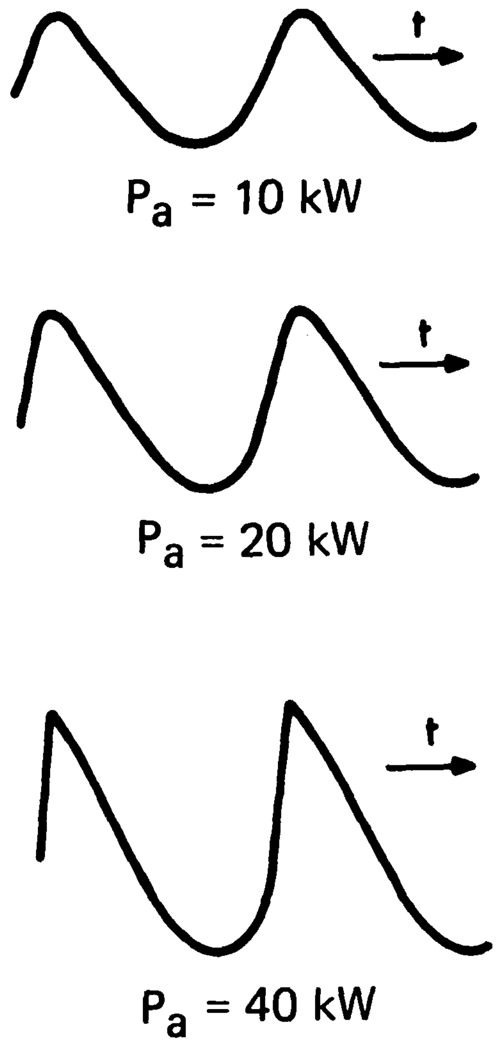

FIGURE 9
WAVEFORMS

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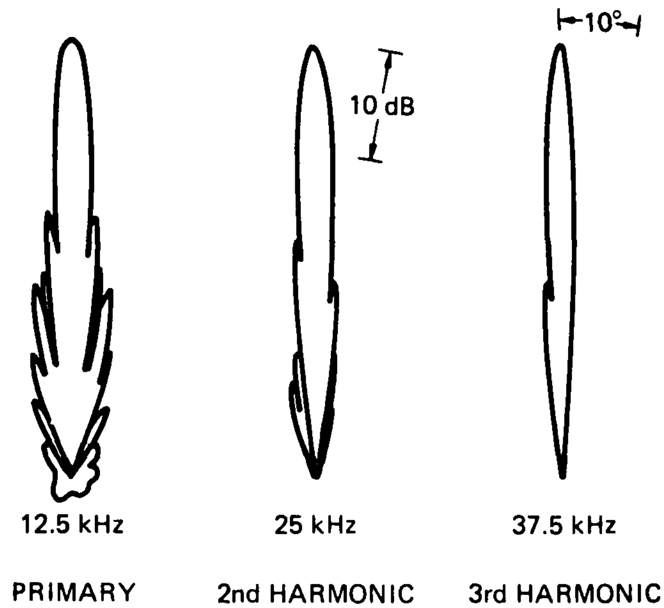

FIGURE 10
HARMONIC BEAM PATTERNS

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How useful are these harmonics? That, of course, depends on their amplitudes, which are, in fact, much higher than the amplitude of the difference frequency radiation. Amplitude data are shown in Fig. 11 for the fundamental, second, and third harmonic of the present experiment when 40 kW of acoustic power is radiated. The second harmonic is down only 10 dB from the fundamental while the third harmonic is down 17 dB. These relatively high amplitudes make the harmonic radiations extremely useful and extend the usable frequency range of the sonar far beyond what the designer could accomplish by any linear approach. There is no reason why the present system could not be used over a frequency range exceeding two decades.

An interesting feature of a nonlinear parametric sonar is its ability to produce highly directed transients. These are known as self-demodulation transients and occur when a short pulse centered at some discrete (primary) frequency is radiated. An example for the present system is given in the photograph of Fig. 12. The upper trace shows a primary pulse energized in a gaussian envelope with a duration of approximately 1 msec. Some distortion in this high frequency waveform can be seen. The important nonlinear feature is the demodulated waveform shown in the lower trace. This signal was received at a distance of 80 m in the low frequency band with a hydrophone having a flat response from 500 Hz to 5 kHz. The form of the low frequency demodulated wave is proportional to the second time derivative of the gaussian envelope. For the demodulated signal in Fig. 12 the peak to peak excursion represents a source level in excess of 210 dB re 1 μPa, when these data are extrapolated from the measurement range of 80 m back to 1 m. If the measurement had been made in the farfield of the parametric array, the signal would have a higher source level. The demodulated signal contains a spectrum of frequency components; the fundamental in this example is about 2.5 kHz. Since the demodulated waveform is a wideband, highly directed entity, it is extremely useful in experiments relating to the philosophy of the impulse response and convolution techniques in signal processing.

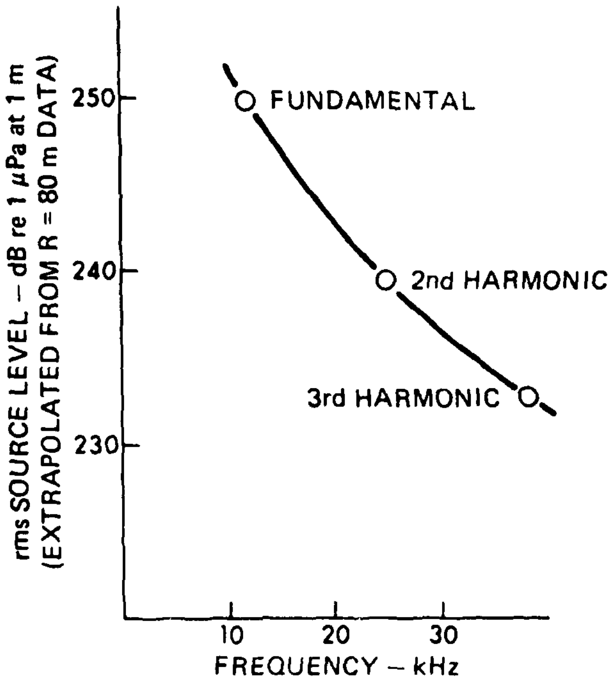

FIGURE 11
HARMONIC SOURCE LEVELS

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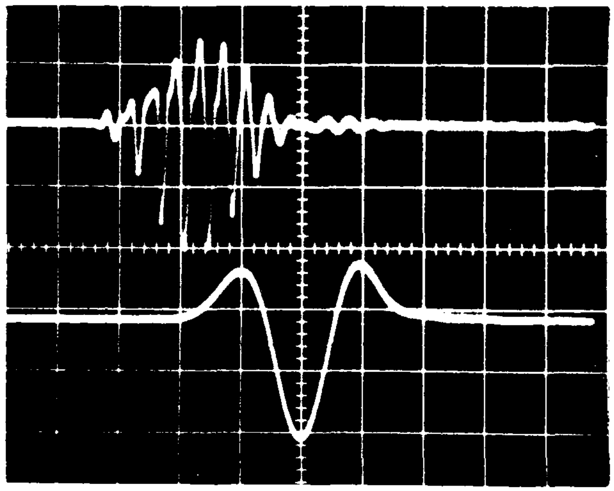

FIGURE 12
SELF-DEMODULATION OF A PRIMARY RADIATION PULSED IN A GAUSSIAN ENVELOPE
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V. APPLICATIONS

Figure 13 is a list of research topics that will be addressed with the parametric system described in this paper. It is beyond the scope of this report to go into detail on any of these topics; however it will be useful to briefly discuss them here to indicate what is expected from this work.

The first topic is mode selection and the influence of thermal structure. A number of previous model studies have shown that the narrow beam parametric array can selectively excite modes in the shallow water waveguide. These studies will be continued at sea in the presence of solar induced thermal structure in the water to evaluate how the model studies translate into the real world.

The next topic is bottom loss comparisons, between continuous wave pings and explosive shots. Many scientists use explosive shots in their research while sonars use pings, and there is significant difference in the resulting signals. We will utilize the present parametric system to compare between shots and pings and explore the relationships in the different types of data acquired. This will help to interpret shot data and lead hopefully to meaningful predictions and extrapolations with respect to sonar.

The third topic, mode conversion over sloped bottoms, is presently an active topic in acoustic propagation. With the present parametric system single propagation modes can be selectively excited. This will permit examination of how they are excited and how they are converted over sloped bottoms within a context of adiabatic mode propagation.

Doppler diversity is important to understanding sonar performance. Measurements of the frequency shifts wrought by currents and wind driven

FIGURE 13
SUMMARY OF
CURRENT SHALLOW WATER ACOUSTICS RESEARCH
PHYSICAL ACOUSTICS DIVISION, ARL:UT

- MODE SELECTION AND THE INFLUENCE OF THERMAL STRUCTURE
- BOTTOM LOSS COMPARISONS (PINGS vs SHOTS)
- MODE CONVERSION OVER SLOPED BOTTOMS
- DOPPLER DIVERSITY IN FORWARD AND BACKSCATTERED SIGNALS
- BIOLOGIC ATTENUATION AND SCATTERING
- BOTTOM PENETRATION BY PARAMETRIC AND LINEAR BEAMS
- REMOTE SENSING OF SEDIMENT PARAMETERS
- ATTAINABLE RANGE RESOLUTION AND BANDWIDTH
- SPATIAL AND TEMPORAL COHERENCE IN PROPAGATING SIGNALS
- SIGNAL PROCESSING ASPECTS OF MODE SELECTION

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surfaces on the highly directive, pure tone signals that are generated by the parametric system will be made to quantify the Doppler diversity of the medium with much higher resolution than heretofore available.

The topic of biologic attenuation and scattering is an old one that will be examined with coherent signals over exceedingly wide frequency ranges, allowing for new contributions in this area.

Bottom penetration of parametric and linear beams has been studied in model tank experiments in the laboratory; results were recently published in the Journal of Sound and Vibration.[1] In these studies we observed the steep penetration of transmitted beams into sediments at angles below the critical grazing angle, in apparent violation of Snell's Law. Theoretical work to resolve the resulting philosophical difficulties has been done and expanded experiments in support of these theoretical formulations will be carried out.

Remote sensing of sediment parameters is of great interest to the oceanographic community. With a narrow beam parametric system, it is possible to construct acoustic refractometers that can measure not only the critical angle in the bottom but also sound velocity in the sediment as well as its reflectivity. This should provide us with a tool to remotely sense the acoustic impedance of the bottom.

The next topic is attainable range resolution and bandwidth. Multimode excitation and intermodal interference in shallow water propagation limit the range of frequencies that can be used. When there are frequency limitations, there are also bandwidth limitations and consequently range resolution limitations. The parametric system will permit us to examine the maximum range resolution attainable in shallow water propagation.

Spatial and temporal coherence in propagating signals is important in signal processing. The medium affects the quality of the signal, which

is measured by its spatial and temporal correlation functions. We will study these functions to determine how the medium affects a signal which might be designed or preferred for use in signal processing.

Signal processing aspects of mode selection refers to the reduction of signal degradation due to the medium by mode selection at the receiver. This is usually accomplished by using a vertical receiving array. With the parametric system described, we will study aspects of (vertical) mode selection of propagating signals with a view toward enhancing their coherence for signal processing.

ACKNOWLEDGMENTS

This work was supported by the U.S. Navy Office of Naval Research.

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